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# The Translation between Functional Requirements and Design Parameters for Robust Design

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## Abstract

The specification of and justification for design parameter (DP) tolerances are primarily based on the acceptable variation of the functions' performance and the functions' sensitivity to the design parameters. However, why certain tolerances are needed is often not transparent, especially in complex products with multi-disciplinary development teams. In those cases, tolerance synthesis and analysis get complicated which introduces ambiguities and difficulties for system-integrators and lead engineers for the objective decision making in terms of trade-offs but also in terms of an efficient computer aided functional tolerancing. Non-optimal tolerances yield potentials for cost improvements in manufacturing and more consistency of the functional performance of the product. In this contribution a framework is proposed to overcome the observed problems and increase the clarity, transparency and traceability of tolerances by analyzing the translation between the DPs and their influence on the final function.

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## 1. Introduction

Mechanical products and systems of all kinds are subject to variations in their parts' and assemblies' dimensions and forms, their materials, their use and their operation environment. However, despite these variations, products are expected to deliver their function and/or aesthetics to a predetermined extent and time to ensure customer satisfaction. To acknowledge the variation in the production phase, i.e. in manufacturing and assembly, part drawings usually contain tolerances on the single dimensions, forms and positions. In most cases these tolerances determine a large share of the cost of production but also of quality assurance. Tighter tolerances might require special production machinery, tooling, metrology equipment and drive the scrap and rework rate of a part; thus the effective analysis and assignment of tolerances as well as robust design can yield great cost saving potentials [1], [2].

The types and magnitudes of the tolerances, i.e. the size of the allowable ranges, are determined by the functional,

technological and esthetical requirements of the product that shall be fulfilled. In highly complex (mechanical) products and systems that require multi-disciplinary development engineering teams (as for example jet engines that need specialists in Design, Fluids, Thermals, Structural Mechanics etc.), the relationship between tolerances and requirements often becomes complicated and non-transparent. This is especially the case when the outputs of one engineering discipline are inputs to another. When setting the tolerances, a whole patchwork of analyses of the influences of all kinds of variations develop where bonus tolerances and process capabilities are also considered in the allocation. Computer Aided Tolerancing (CAT) is utilized for tolerance synthesis and analysis [3], [4]. However, CAT is often limited to geometrical requirements like lengths, gaps and clearances as functional requirements [5]. The most common methods are tolerance chains and sensitivity analysis using experiments or simulations depending on the individual function. Due to the nature of multi-disciplinarity these analyses often stand separately and independently. An important challenge in a

multi-disciplinary industrial application is that the engineers use different vocabularies for the requirement and problem specifications. Furthermore, for the specification of interface requirements often product characteristics (e.g. large width) are used instead of the required properties (e.g. high stiffness). As for the nominal dimensions that are being passed from discipline to discipline, the same happens to the tolerances and safety factors. The justification of tolerances is not very transparent making it difficult for system integrators and lead engineers to challenge the design and prioritize necessary additional analyses. Also, for drawings of parts that have been produced for years it is often the case that the justification of tolerances cannot be reconstructed and it is not understood what functions certain dimensions contribute to. In addition, the re-use of modules or components as part of a platform strategy may leave tolerance justifications running over multiple product lines. This all leads to a strong hesitation regarding changes to the parts due to unknown risks associated with those (see for example the GM ignition switch recall case [6]).

The translation between the design parameters (DPs) or external noise factors (NFs) and the functional requirements (FRs) is an established way to map the behavior of a product or system. The Robust Design Methodology (RDM) uses these transfer functions to derive sensitivities of functions to DPs and NFs to optimize the performance and predictability of the final product [2]. The setting of tolerances is directly linked to the sensitivity of the functions to the single DPs. RDM and the mapping between FRs and DPs are more or less explicitly done by the individual engineering disciplines. However, in the case of a complex and highly integral system, effects that go beyond a specific function or sub-function can be difficult to oversee. The mapping gets complicated and impractical in these instances making it difficult to have efficient tolerance design and allocation. “Information modelling is critical to the integration of design and tolerancing” [7].

The question arises of how the clarity and transparency of tolerances as well as their impact and severity on the final functional performance can be captured in a practical way.

In this contribution we address the encountered problem by proposing a framework on how to look at tolerances to support the specification and justification of tolerances for a robust design. Based on comprehensible decomposition and structuring of functional requirements and their design parameters a target-oriented communication between engineers of multi-disciplinary teams is supported. The framework enables the specification and justification of tolerances but also the setting of nominal dimensions across different disciplines and can give the basis for more advanced tolerance optimization within CAT.

## 2. Previous work

The idea of systematically mapping the dependencies of functions to design parameters and their tolerances is widely established in the engineering design community and is usually referred to as requirement or system decomposition. A framework that largely makes use of decomposition is

Axiomatic Design (AD) by Nam P. Suh [8]. AD promotes not only the mapping between FRs and DPs but also the mapping from customer attributes (Customer domain) to the functional requirements and the mapping between design parameters and process variables in the process domain. The decomposition of the high level functional requirements and how these are addressed in the physical domain is realized by so called zigzagging between the functional and physical domain. With this, new evolving lower level requirements and design parameters are systematically established and a design solution generated. The function-means tree model as described by Hansen and Andreasen [9] works in a similar fashion arranging the functions and their realizations in a hierarchical manner. Söderberg and Johanneson [10] utilize function-means trees to detect potential tolerance chains to increase robustness. However, these techniques are more an idealized process that is often not practical, especially if the product is complex or solutions are being reused. Another framework that is more tailored towards the management of variation in design and manufacturing is the Variation Risk Management (VRM) framework by Thornton [11]. The framework is generally divided into three phases: Identification, Assessment and Mitigation. The identification of potential issues related to variation followed by the assessment of the associated risks as well as costs and the final mitigation of the issues with the most potential forms a holistic approach. In that way, trade-offs between design and manufacturing can efficiently and objectively be managed to improve the quality and cost of the final product. With respect to the systematical tackling of the issues, the identification phase comprising the collection of variation-sensitive requirements and the risk flow-down to understand the structure of the product are of high importance. “The risk flow-down is an iterative decomposition process that identifies a hierarchy of contributing assembly, subassembly, part and process parameters [12].” Dantan et al. [1] propose an information model capturing the causality of Manufacturing Process Key Characteristics and Part/Product Key Characteristics to manage manufacturing resources and tolerances. The House of Quality (HoQ) methodology in Quality Function Deployment (QFD) has a similar domain based structure as Axiomatic Design [13]. It maps the customer attributes through the parts and process domain to the production domain. The decomposition of the attributes is facilitated by relating the “whats” to the “hows”. “What” is the requirement and “how” is it addressed. The “hows” are turned into “whats” for every level of decomposition in a new “house”. The Integrated Tolerancing Process (ITP) as presented by Dantan et al. [7] addresses the functional decomposition of tolerances through geometrical requirements and decomposed functions. Howard et al. [14] proposed the Variation Management Framework (VMF) emphasizing the mapping of variation and sensitivities through the domains for robust design. Hansen [15] and Weber [16] presented further product and process representations describing the relationship between requirements and product characteristics considering external influences. Methods like FMEA (Failure modes and effects analysis) and RCA (Root conflict analysis) use decomposition

techniques to find the root causes for failures or potential failures.

### 3. Translation between FRs and DPs – a proposal for a new framework

The frameworks and methods discussed in the previous section are widely accepted and have proven to be useful in design and failure analysis situations. However, for the daily engineering development work and especially the detailed tolerance design and analysis phase, frameworks like Axiomatic Design and the House of Quality are too generic and impractical for addressing the issues mentioned in the introduction. Tools like FMEA and RCA can be of an appropriate level of detail but are, however, too focused and therefore limited to failures. The VRM framework on the other hand gives a good guidance to break down the product key characteristics to the related process characteristics. However, VRM is limited to dimensions that can be measured on the shop floor and in the assembly line and is therefore very production focused. Abstract functional and emerging properties like “mechanical stiffness” or “efficiency” are not addressed.

The purpose of the proposed framework in this contribution is to adapt and extend the VRM to include functional and emerging properties of a product. With this, it is believed, the communication between different engineering disciplines regarding dimensions and their tolerance can be made more understandable, traceable and transparent also for non SMEs (subject-matter experts) like system integrators and managers. The derivation of the framework is driven by the question of how to map between functional requirements and design parameters most efficiently. The idea is to ease the mapping and therefore extend the existing methods described in Section 2. Consider the “easy” example of a cantilever beam with a rectangular cross-section, where the functional requirement is a specific maximum deflection  $\delta_{max}$  at the far end under a load  $F$ . For this case an analytical expression can be derived as:

$$\delta_{max} = \frac{F \cdot l^3}{3 \cdot E \cdot \frac{b \cdot h^3}{12}} \quad (1)$$

The equation includes all influencing dimensional, material and load parameters. A design engineer could now for example insist on a specific height  $h$  of the beam to limit the maximum deflection of the beam. With constraints maybe only on the length and the material of the beam, the actual interest is in the second moment of inertia  $I$  rather than only the height.

$$I = \frac{b \cdot h^3}{12} \quad (2)$$

A wrongly / too simplistic formulation of the requirement unnecessarily constrains the solution space and can cause a

non-optimal dimensioning and tolerancing. This clarification eases the mapping between FR and DPs and increases the understanding of what properties are actually required. The complicatedness of the transfer function rises with the complexity and level of abstraction of the functional requirement and can hence also be reduced.

Figure 1 illustrates the mapping between a functional requirement and a contributing design parameter (for simplicity only one DP is shown, in most cases a FR is dependent on multiple DPs). As in the example of the deflection of the cantilever beam, it is often helpful for the communication and traceability not to map the FR directly to the corresponding DPs but introduce sub-functional requirements (SFRs) in between. Especially abstract FRs like for example efficiency and acceleration can have complicated dependencies with numerous DPs. Decomposition into SFRs can help to express actual requirements for a function.

The translation between FRs, SFRs and DPs can be done from the ‘selection of concept’ onwards. In the early phases the translation might be based on analytical descriptions and first order principles of the function. First statements about the importance and sensitivities of SFRs and DPs can be made. As the design matures the mapping can be detailed including data from experiments and simulations.

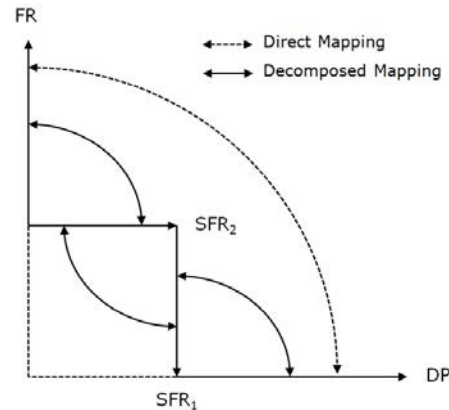


Figure 1: Mapping between FR and DP

To formalize the framework and the introduction of SFRs a bottom-up approach has been chosen to derive the different levels of SFRs starting at the sources of variation, which are dimensional, material, external (loads and environment) and time-related. Further, the P-Diagram (Figure 2) is used to structure the different sources of variation. The product is defined by its single DPs (control factors). This very basic level of definition is used on technical drawings of physical parts and assemblies. Nominal geometrical dimensions and form attributes as well as required material and surface properties are defined including their allowable deviations and tolerances. The most basic functional requirements are directly on these lowest level DPs and we define these as Level 1 SFR. Resulting from customer surveys, for example, a company developing a smart phone sets certain requirements on the width and length as well as the “feel” (material and surface) of the phone. These requirements are directly linked to the housing of the phone and are prescribed

on its drawing. Level 2 SFRs combine properties of multiple dimensions, like required volumes or area moments, but also relative sizes and positions in assemblies. Examples for Level 2 requirements are the capacity of an engine and the position of a button on a phone.

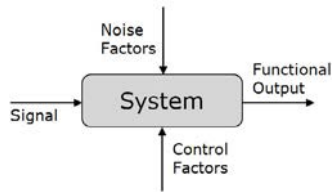


Figure 2: P-Diagram

The level of abstraction is further increased for the 3<sup>rd</sup> level SFRs. Combining dimensions and material properties yields for example part or assembly properties like weight, stiffness and rigidity. SFR levels 1-3 entail the physical properties of a product or system and build logically on top of each other. For example, to derive the weight of a part, its volume and density needs to be known, which again implies that all single dimensions are known. For level 4 SFRs external non material or geometrical factors, like for example temperature, load or flow, are included. Some physical phenomena are time dependent such as creep, wear and corrosion. The variable time is included in level 5 SFRs. All other SFRs and functional responses and properties of higher complexity can be derived as aggregations of level 1- 5. Level 6 comprises of all higher level functional requirements including advanced

emerging responses like efficiency, power etc. Table 1 summarizes the proposed framework with examples for mechanical properties. Higher level sub-functional requirements are by inherent nature more complex and less restricting than lower level SFRs. The association of each tolerance to their respective SFR and functional origin in a database can increase the clarity, transparency and traceability and can support an efficient CAT.

## Application

To ensure the applicability of a framework like the proposed decomposition of functional requirements, the Pareto Principle should be followed. Rather than having an exhaustive break down of all influencing parameters and properties of a function, the focus should be on the most influential characteristics and properties of a design towards the functional requirements. The idea of this framework and approach of looking at tolerances is to increase the understanding and traceability. Therefore, the highest meaningful level of SFR should be used to communicate acceptable ranges for the individual functions. In that way the design is also not being constrained more than necessary. Knowledge and experiences from previous projects as well as results from analyses can be utilized to formulate the SFRs. It shall be stressed here that usually no additional analyses and tests need to be run. The data that is anyway being produced for design, verification and validation shall be utilized to express the SFRs.

Table 1: Description of Sub-Functional Requirement Levels

| SFR                                       | Sources of Variation  | Examples (mechanical)   |
|---|---|---|
| Control Factors<br>(Design<br>Parameters) | Level 1 Single Dimensions and Material Properties<br>(Basic definitions on drawing) | <ul style="list-style-type: none"> <li>Geometrical dimensions</li> <li>Forms (GD&amp;T)</li> <li>Material properties (Density, yield stress/strain, Young's modulus, conductivity, resistance...)</li> <li>Surface finish</li> </ul>      |
|   | Level 2 Multiple Dimensions   | <ul style="list-style-type: none"> <li>Volume, Area</li> <li>Aspect ratio</li> <li>Moment of inertia</li> <li>2nd Moment of area</li> <li>Assemblies (relative dimensions, positions, orientations, flushness, gaps, overlaps)</li> </ul> |
|   | Level 3 Dimensions & Material Properties  | <ul style="list-style-type: none"> <li>Weight</li> <li>Stiffness</li> <li>Rigidity</li> </ul>   |
| Use<br>(Signal & Noise<br>Factors)        | Dimensions & External Factors   | <ul style="list-style-type: none"> <li>Stress</li> </ul>  |
|   | Level 4 Material Properties & External Factors                                      | <ul style="list-style-type: none"> <li>Thermal Expansion (relative)</li> </ul>  |
|   | Dimensions & Material Properties & External Factors                                 | <ul style="list-style-type: none"> <li>Thermal Expansion (absolute)</li> <li>Bending, buckling, distortion</li> <li>Compression</li> </ul>  |
| Time                                      | Level 5 Dimensions & Material Properties & External Factors & Time                  | <ul style="list-style-type: none"> <li>Creep</li> <li>Corrosion</li> <li>Wear</li> </ul>  |
|   | Level 6 Emerging responses and properties<br>(combining Level 1 – 5)                | <ul style="list-style-type: none"> <li>Friction</li> <li>Efficiency</li> <li>Power, Energy</li> </ul>   |

Once the SFRs for all functions are defined, they can be compared and analyzed by system integrators or lead engineers to make the trade-offs for working out the final tolerances of the dimensions on the part drawings. Design Structure Matrices can be used as a structured way to capture all SFRs.

#### 4. Example – The Glue Gun

The proposed framework and way of thinking about tolerances shall be demonstrated in a simple example. Note that the advantages and usefulness of the proposed framework arise with a higher product complexity and multi-disciplinarity. The example is chosen to illustrate the general idea. Figure 3 shows the principle model of a glue gun [17]. By pulling the trigger (green) the grabbing arm (red) clamps the glue stick onto the sledge and subsequently drags it forward to feed the heating unit that finally dispenses the glue. Depending on the way of argumentation, the framework can be used in a bottom-up or top-down fashion. To investigate, for example, the origin or the functional impact of tolerances it is practical to review the SFRs bottom-up, whereas for the design and tolerance synthesis a top-down approach breaking down the functional requirements to SFRs using experience, analytics, experiments and simulations is appropriate. “Thought experiments” like the virtual deviation method [18] can also help to identify the most influencing parameters. For the glue gun example a top-down approach is demonstrated in the following. For simplicity reasons it is assumed that there are only two main functional requirements for the glue gun: 1) the application force for the user (for example  $8 \pm 2$  N) and 2) the precise and predictable delivery of glue (for example

$0.5 \pm 0.1$  ml/stroke). Table 2 summarizes the decomposition of the two functional requirements.

The application force is mainly driven by two phenomena: firstly the friction of all moving parts and secondly the general gearing of the mechanism itself.

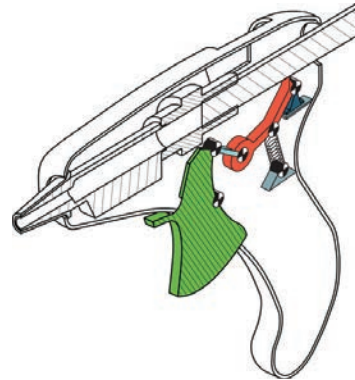


Figure 3: Glue Gun Principle Model

The friction is a complex phenomenon depending on the materials, the applied force but also on relative sizes, positions and orientations of the single parts. Another influence is the level of compliance in the system. Using the breakdown to SFRs as proposed in the previous sections helps to identify the actual attributes and properties influencing the application force for the glue gun and to prioritize further analyses as appropriate. For the allocation of tolerances, the constraints on the highest possible level of SFR should be used to constrain the design as little as possible.

Table 2: Functional Requirements Breakdown for Glue Gun Example

|         | Constant application force (+ no jamming)  | Precise and predictable delivery of glue (Linear translation between trigger and feed)  |
|---------|--|---|
| Level 6 | Friction of moving parts   | Slip of glue stick: friction of hook to glue stick > rubber heater inlet to glue stick and vice versa for retraction  |
| Level 5 | n.a.   | n.a.  |
| Level 4 | <ul style="list-style-type: none"> <li>Bending, buckling, distortion, deformation of mechanism parts</li> </ul>  | <ul style="list-style-type: none"> <li>Bending, buckling, distortion, deformation of mechanism parts</li> </ul>   |
| Level 3 | <ul style="list-style-type: none"> <li>Stiffness of mechanism parts</li> </ul>   | <ul style="list-style-type: none"> <li>Stiffness of mechanism parts</li> </ul>  |
| Level 2 | <ul style="list-style-type: none"> <li>Sledge width to rail width</li> <li>Ø glue stick to Ø heater, Ø nozzle, Ø rubber hole, clamping arm length, Ø sledge pass through, Ø housing hole</li> <li>Hole positions of joints</li> <li>Alignment of sledge and rail (housing halves relative position)</li> <li>Alignment of sledge and heater</li> <li>Moments of inertia of mechanism parts</li> <li>Aspect ratios of lever arms</li> </ul> | <ul style="list-style-type: none"> <li>Ø pin to Ø hole of joint connections</li> <li>Sledge width to rail width</li> <li>Moments of inertia of mechanism parts</li> <li>Gaps in joints (wiggle room)</li> <li>Gap between rail and sledge</li> <li>Aspect ratios of lever arms (gearing ratio)</li> </ul> |
| Level 1 | <ul style="list-style-type: none"> <li>Parts' E-modulus</li> <li>friction coefficients</li> <li>Spring constant</li> <li>Dimensions of mechanism parts</li> </ul>  | <ul style="list-style-type: none"> <li>Parts' E-modulus</li> <li>Dimensions of mechanism parts</li> </ul>   |



In that way the design can also more easily be assessed and challenged by non-SMEs, i.e. system integrators and lead engineers. If, for example, bending and buckling of the mechanism turns out to have a major influence on the application force, the constraints and tolerances should be set and communicated on that level, ensuring the understanding for tolerances but also leaving design space to change the design and material while complying with the constraints on bending and buckling. The second main functional requirement, the precise and predictable delivery of glue, is dependent on the smooth and linear translation between trigger and feed sledge. The most important characteristics are the gearing of the mechanism, the level of compliance and the prevention of slip of the glue stick. Again, the highest level requirements should be selected to communicate the SFRs and to set the tolerances.

## 5. Discussion and concluding remarks

In this contribution we propose a new framework of how to translate between functional requirements and design parameters through sub-functional requirements to improve the specification and justification of tolerances. Expressing the sub-functional requirements leads to a less constrained design. Compared to traditional tolerancing frameworks that focus on interfaces and resulting positions and orientations of parts in assemblies [19], the presented framework captures also functional emerging properties taking material properties, external factors like forces and temperature as well as time related factors into account. Tolerance methods that do take functional responses into account are mostly concerned with tolerance analysis or allocation and optimization [4], which require very detailed models which, again lack transparency and traceability. With the proposed approach a clear traceability of tolerances can be ensured linking them to the respective SFRs, which can be done in a less complicated way than to the overall FR. The framework also yields potentials in improving the communication about and the finding of design trade-offs especially in multi-disciplinary designs as well as the extension of computer aided functional tolerancing to properties of higher abstraction. Positive impacts can also be seen on change management and propagation, design documentation including reasoning as well as motivation and decision support in terms of decision rational. Knowing the main influencing attributes and properties also helps robust design and design optimization. Furthermore, the SFRs can directly be compared to customer requirements and product specifications as well as potentially be used for testing and verification purposes.

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